

How long will it take? Conceptualizing the temporal dynamics of energy transitions

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Original research article

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ABSTRACT

Transitioning away from our current global energy system is of paramount importance. The speed at which a transition can take place—its timing, or temporal dynamics—is a critical element of consideration. This study therefore investigates the issue of time in global and national energy transitions by asking: What does the mainstream academic literature suggest about the time scale of energy transitions? Additionally, what does some of the more recent empirical data related to transitions say, or challenge, about conventional views? In answering these questions, the article presents a “mainstream” view of energy transitions as long, protracted affairs, often taking decades to centuries to occur. However, the article then offers some empirical evidence that the predominant view of timing may not always be supported by the evidence. With this in mind, the final part of the article argues for more transparent conceptions and definitions of energy transitions, and it asks for analysis that recognizes the causal complexity underlying them.

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1. Introduction

Transitioning away from our current global energy system is of paramount importance [1]. As Grubler compellingly writes, “the need for the ‘next’ energy transition is widely apparent as current energy systems are simply unsustainable on all accounts of social, economic, and environmental criteria [2]”. And as Miller et al. add, “the future of energy systems is one of the central policy challenges facing industrial countries [3]”. Unfortunately, however, neither private markets nor government agencies seem likely to spur a transition on their own [4]. Moreover, transitions to newer, cleaner energy systems such as sources of renewable electricity [5,6] or electric vehicles [7,8] often require significant shifts not only in technology, but in political regulations, tariffs and pricing regimes, and the behavior of users and adopters.

The speed at which a transition can take place—its timing, or temporal dynamics—is a vital element of consideration. According to the International Energy Agency, for example, if “action to reduce CO₂ emissions is not taken before 2017, all the allowable CO₂ emis-

sions would be locked-in by energy infrastructure existing at that time [9]”. In other words, if a transition does not occur quickly, or soon, it may be too late. Giddens went so far as to call this the “climate paradox”, the fact that by the time humanity may come to fully realize how much they need to shift to low-carbon forms of energy, they will have already passed the point of no return [10].

This study, therefore, investigates the critical issue of time in global and national energy transitions. Although other elements of transitions such as their scale, magnitude, direction, drivers, actors, and mechanisms are touched upon when exploring this theme, the article’s central purpose is to ask: What does the mainstream academic literature suggest about the time scale of energy transitions? In addition, what does some of the more recent empirical data related to transitions say, or challenge, about the mainstream view?

In answering these questions, the article proceeds as follows. It begins by presenting a mainstream view of energy transitions as long, protracted affairs, often taking decades to centuries to occur. Part of this argument draws from the history of previous major energy transitions such as the switch from wood to coal or coal to oil. Part of this argument also draws on the sheer scale and complexity involved in major transitions, as well as the tendency for new systems to face the “lock-in” or “path dependency” of existing systems. However, the article then offers some empirical evidence that the predominant view of timing may not always be supported by the evidence. The second half of the paper shows that there have

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Table 1
Five definitions of energy transitions.

| Definition | Source |
|---|--------------------------|
| A change in fuels (e.g., from wood to coal or coal to oil) and their associated technologies (e.g., from steam engines to internal combustion engines) | Hirsh and Jones [22] |
| Shifts in the fuel source for energy production and the technologies used to exploit that fuel | Miller et al. [23] |
| A particularly significant set of changes to the patterns of energy use in a society, potentially affecting resources, carriers, converters, and services | O'Connor [24] |
| The switch from an economic system dependent on one or a series of energy sources and technologies to another | Fouquet and Pearson [25] |
| The time that elapses between the introduction of a new primary energy source, or prime mover, and its rise to claiming a substantial share of the overall market | Smil [26] |

been many transitions—at varying scales and sectors—that have occurred quite quickly—that is, between a few years and a decade or so, or within a single generation. At smaller scales, the adoption of cookstoves, air conditioners, and flex-fuel vehicles are excellent examples. At the state or national scale, almost complete transitions to oil and electricity in Kuwait, natural gas in the Netherlands, and nuclear electricity in France took only a decade, roughly, to occur. This part of the article presents ten case studies of energy transitions that, in aggregate, affected almost one billion people and needed only 1–16 years to unfold. Clearly, this evidence suggests that some energy transitions can occur much more quickly than commonly believed.

2. Energy transitions: conceptualizations from the literature

This section of the article presents a “mainstream” view of energy transitions drawn mostly from the academic and policy literature about transitions. It introduces definitions and statements about the timing behind transitions and discusses how the historical record confirms these conceptualizations. It also illustrates the complexity, phases, and path dependent nature of energy transitions.

2.1. Definitions, timing, and contextual specificity

As Table 1 reveals, although there is no standard or commonly accepted definition of an energy transition in the recent academic literature, there is a common theme within them. An energy transition most broadly involves a change in an energy system, usually to a particular fuel source, technology, or prime mover (a device that converts energy into useful services, such as an automobile or television) [11–14]. Some studies choose to focus only on the first of those dimensions—fuels such as oil, coal, gas, and uranium—causing some to critique that they narrowly frame transitions as a way of foreclosing future change [15] or of masking “the social and political dimensions of energy systems behind a false veneer of limited technological choices [16]”. Others take a broader view that encompasses shifts in technology as well as the resulting “constellation of energy inputs and outputs involving suppliers, distributors, and end users along with institutions of regulation, conversion and trade [17]”, or structural changes in the way energy services are delivered. Still others argue that the term “energy transition” is meant to be similar to energy “transformation” or “revolution”, a disruptive or radical transformation of both technology and social practices [18–20], often centered on expanding access to energy, or abundance, but occasionally focused on scarcity [21].

Transitions, perhaps obviously, must be measured over time, usually from the point at which an energy system or technology occupies a 1% market share and then grows or shrinks accordingly. As Melosi puts it, “The concept of ‘energy transitions’ is based on the notion that a single energy source, or group of related sources, dominated the market during a particular period or era, eventually to be challenged and then replaced by another major source or sources [18]”. Smil even puts a definitive threshold to his definition, arguing that an energy transition refers to the time that elapses between the introduction of a new fuel or prime mover” and its rise to 25% of national or global market share [26]. So does Grubler, who argues that “grand transitions” can occur when they reach 50% of a market [27].

Complicating matters, in some circumstances what may seem a sweeping transition or radical transformation can actually be a bundle of more discrete conversions. As O'Connor concludes, “Big transitions are the sum of many small ones. Looking at overall energy consumption will miss the small-scale changes that are the foundation of the transitions [28]”. The big ascent of oil at the start of the previous century, for example, can also be interpreted as a series of less grand changes involving:

- The switch from animal power to internal combustion engines for private vehicles, and the social rejection of electric vehicles [29];
- The conversion of steam engines on ships and locomotives to diesel for marine vessels and trains [30];
- The shift from candles and kerosene for lighting to oil based lamps [31];
- The adaptation of coal boilers to oil boilers for the generation of electric power [32];
- The exchange of wooden fireplaces and coal stoves to oil and gas furnaces in homes [33].

Similarly, a transition in the United States to air conditioning, explored in greater detail below, was actually the result of concurrent innovations in air circulation, heat exchangers, heat pumps, halocarbon refrigerants, customization and mass production, and marketing [34]. It is occasionally these “minor transitions” that, when they occur in a concerted manner, create the “major transitions” that are so easily identifiable.

Sometimes, however, measuring a transition is more complicated than it may seem. An energy system can grow rapidly in an absolute sense but still fail to grow in a comparative sense. Hydroelectricity in the United States was a low-cost source of energy in the 1950s and 1960s, where it grew in capacity threefold from 1949 to 1964. However, during this time, because other sources of energy (and demand for electricity) grew faster, hydropower's overall national share dropped from 32% to 16%. Similarly, from 2000 to 2010, global annual investment in solar PV increased by a factor of 16, investment in wind grew fourfold, investment in solar heating threefold. This sounds impressive—yet the overall contribution of solar (heating and PV) and wind to total global final energy consumption grew from less than one-tenth of one percent to slightly less than 1% over the same period [35,36], a proverbial drop in the bucket.

In other situations, the rise of an energy system may depend, or be mutually dependent on, another—meaning it can be a mistake to identify or analyze a single energy system or technology by itself. Occasionally, two shifts have to occur to result in one combined effect, since the one tends to require in tandem the adoption of the other. As Fig. 1 illustrates, Grubler found this to be the case with technologies such as the railway and the telegraph as well as the road network for automobiles and oil pipelines [37].

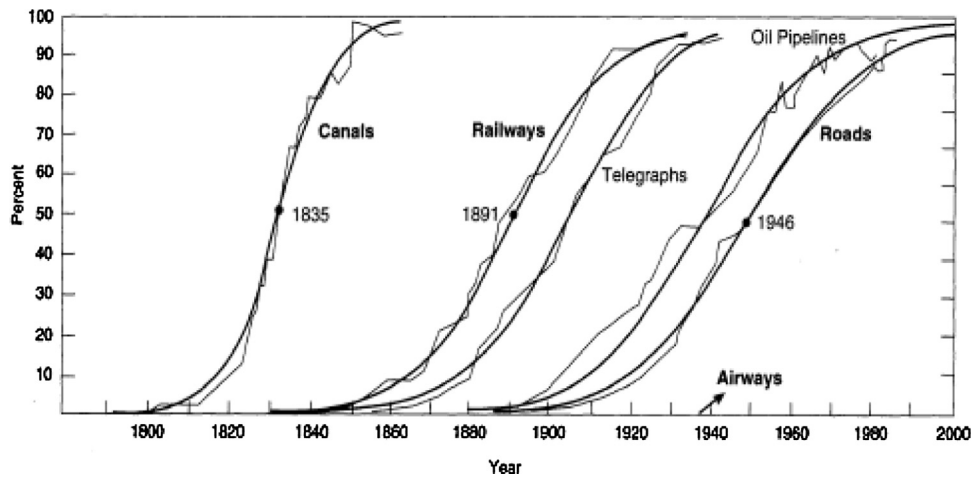


Fig. 1. Growth of Infrastructures in the United States as a Percentage of their Maximum Network Size.

Source: Ref. [38]

Table 2

The differences in timing and speed of energy transitions in Europe.

| Phase-out traditional renewables phase-in coal: | | Diffusion midpoint | Diffusion speed |
|---|-------------|--------------------|-----------------|
| Core | England | 1736 | 160 |
| | Germany | 1857 | 102 |
| Periphery | France | 1870 | 107 |
| | Netherlands | 1873 | 105 |
| | Spain | 1919 | 111 |
| | Sweden | 1922 | 96 |
| | Italy | 1919 | 98 |
| Periphery | Portugal | 1949 | 135 |
| Phase-out coal phase-in oil/gas/electricity: | | | |
| Core | Portugal | 1966 | 47 |
| | Italy | 1960 | 65 |
| Rim | Sweden | 1963 | 67 |
| | Spain | 1975 | 69 |
| | Netherlands | 1962 | 62 |
| | France | 1972 | 65 |
| | Germany | 1984 | 50 |
| Periphery | England | 1979 | 67 |

Source: Ref. [39]

2.2. Phases, path dependency, lock-in and subversion

The mainstream literature on energy transitions has also advanced a number of interrelated concepts that are helpful in understanding why transitions are expected to take so much time. One of them is the notion of “phases”. Grubler has posited that major European energy transitions since 1800 all went through phases of having a core or innovation center, where that innovation began, moving upward to early adopters (what he called the rim) to, lastly, the late adopters, which he classified as the periphery [39]. His data suggests that the time it took to transition from pre-industrial biomass (“traditional renewables”) to coal—the time needed for coal to pass through all three phases of core, rim, and periphery—ranged from 96 to 160 years, as Table 2 reveals. The shift again from coal to oil and electricity was more rapid, but it still ranged from 47 to 69 years for those technologies to pass through the three phases.

During these transitions, two things are of note. One is that a tension existed between early and late adopters, with each of them confronting separate sets of advantages and risks. The idea here is that transition or technology adoption will rarely be uniform, and will occur in fits and starts—leading to inconstant rates of change. Another is that transitions can involve at times not necessarily “going towards” something but instead “moving away” from

it. Or, as Grubler remarked, history in Europe reveals a pattern of “first in, last out; and last in, first out” with respect to the lifecycle of related energy technologies and systems. That is, sometimes late adopters stick with the technology even past its point of competitiveness or attractiveness—taking a longer time. In other situations, early adopters overinvest in a technology and get stuck, finding it difficult to get out compared to latecomers.

Further complicating matters, Grubler hypothesized another number of factors that can complicate—and thus extend—the time needed for a transition to occur [37]. One is that no innovation spreads simultaneously, instead all undergo a typical S shaped temporal pattern that takes months, years, or even decades to occur. One is that diffusion is a spatial as well as temporal phenomenon, meaning that it will take time for an innovation or new system to transit from the center to the periphery. One is that the density of adoption will differ based on a variety of contextual factors, making adoption a process of “clusters and lumps” rather than a straight line.

Drawing from Grubler’s work, Wilson presented a conceptualization of phases in his analysis of successful “scaling-up” exercises for various prime movers and types of energy equipment such as wind turbines, solar panels, automobiles, oil refineries, and natural gas power plants [40]. Across these various types of energy systems, he concluded that four phases must occur in order:

- An extended period of experimentation and learning with small unit-scale technologies and a diversity of designs, with industry scale being generally small and diverse;
- Scaling-up at the unit level as designs are improved and economies of scale begin to emerge;
- Scaling up at the industry level, epitomized by the phrase “sell many, and large units in core markets” as well as a “crowding out” of smaller competitors;
- As industry structure becomes standardized and core markets become saturated, further industry growth is driven by globalization, the diffusion of a successful design from the innovation core to rim and periphery markets.

In sum: each of these individual phases requires require substantial time and are sequential rather than simultaneous, explaining thus the many decades-long pace under which energy transitions unfold [41].

Using a different approach, in his historical work *Networks of Power* [42] Hughes explored the evolution of the small intercity lighting systems of the 1880s into the regional power systems

of the 1920s. Drawing heavily from a non-engineering approach to systems theory, Hughes argued that the electric utility system – like all large technical systems – progressed through five other types of phases, each one taking a meaningful amount of time [43].¹ First came invention and development, where inventor-entrepreneurs invented a product and enrolled engineers and financiers to their project. Second came technology transfer, where successful technologies were exported between societies. Third came system growth, where reverse salients were solved and the system operators managed challenges. Fourth came momentum, where the system acquired velocity. Fifth came style, where the system operators became particularly adept at solving problems in their own way, creating technological differentiation. In his later work, Hughes elaborated that the process took a long time (decades) and also that it tended to create a path dependency that resists change. The “momentum” of a given system referred to the machines, structures, and physical artifacts where capital had been invested in a technology; the persons whose professional skills were attached, trained, and associated with a technology; and the business interests and political concerns connected to a large-scale sociotechnical system. Taken together, these elements form the system’s rate of growth, which often accelerates. Put another way, large sums of labor, capital, and effort are “sunk” into existing socio-technical systems so that they create their own “inertia” [44] or “lock-in” which highly resist change [45]. As Lund notes, “the inertia of energy systems against changes is large, among others because of the long investment cycles of energy infrastructures or production plants [46]”.

An additional factor contributing to path dependence can be the strategic capture, cooption, or “subversion” of a new energy system or idea. Byrne and Rich propose that rather than sit idly by and accept a new innovation, many incumbent actors will try to contain or coopt it [47]. That is, they will concede the need for change but then attempt to direct resources or capital back into their own energy systems. One particularly pernicious practice is the suppression of patents, where some energy companies actively suppress new and innovative technologies that threaten to disrupt profits in a market [48–51]. Stirling also argues that energy transformations can become subverted by dominant interests—who attempt to capture the drivers or discourses behind them with options that will directly benefit them, with shale gas, carbon capture and storage, nuclear power, and climate change geoengineering serving as examples [52,53].

In order to counteract path dependence, inertia, and lock-in, scholars looking at transitions theory have argued that truly transformative change must be the result of alterations at every level of the system simultaneously. That is, one must alter technologies, political and legal regulations, economies of scale and price signals, and social attitudes and values together. A widely cited theoretical manifestation of these ideas is encapsulated in a framework known as the “multilevel perspective” on socio-technical transitions and innovation [54–58]. This suggests that transitions occur through interactions between three levels: the niche, the regime, and the landscape. The idea is that that niche-innovations often face uphill struggles against existing systems. The “landscape” refers to exogenous developments or shocks (e.g. economic crises, demographic changes, wars, ideological change, major environmental disruption like climate change) that create pressures on the regime, which in turn create windows of opportunity for the diffusion of niche-innovations.

A key term of art within the framework is that of a “transition pathway”. Analytically, the claim is that different kinds of interactions between niche, regime and landscape result in different kinds of alignments. Geels and Schot constructed a typology based on combinations between two dimensions: the timing and nature of multi-level interactions [59]. This led them to distinguish four transition pathways: (1) technological substitution, based on disruptive niche-innovations which are sufficiently developed when landscape pressure occurs, (2) transformation, in which landscape pressures stimulate incumbent actors to gradually adjust the regime, when niche-innovations are not sufficiently developed, (3) reconfiguration, based on symbiotic niche-innovations that are incorporated into the regime and trigger further (architectural) adjustments under landscape pressure, (4) de-alignment and re-alignment, in which major landscape pressures destabilize the regime when niche-innovations are insufficiently developed; the prolonged co-existence of niche-innovations is followed by re-creation of a new regime around one of them. The implication is that transitions are competitive – many niches fail – and that existing energy systems and infrastructure can dominate and suppress threatening innovations.

Indeed, the idea that energy transitions will take a substantial amount of time is embedded in no less than four major academic theories or approaches—each with their different foci, units of analysis, and concepts—shown in Table 3, including the multilevel perspective as well as three others from the disciplines of environmental science, sociology, and political ecology. Socio-technical transitions scholars focus on how to counteract the momentum or domination of existing systems [60,61]; ecological modernists highlight the lengthy process of regulatory reform [62–64]; sociologists underscore how altering everyday routines and practices can take a generation [65–69]; political ecologists proclaim how neo-liberal ideology has further entrenched capitalism into our social and political spaces so that alternatives are rarely imagined let alone implemented [70–74]. The end result is that energy transitions, breaking out of these embedded systems, require a “long-term transformation” that is “a messy, conflictual, and highly disjointed process [75]”.

2.3. Conceptualizing the temporal dynamics of historical transitions

Independent of these theories and concepts, the historical record does seemingly support the mainstream view that energy transitions all take time. In the United States crude oil took half a century from its exploratory stages in the 1860s to capturing 10% of the national market in the 1910s, then 30 years more to reach 25%. Natural gas took 70 years to rise from 1% to 20% in the United States. Coal needed 103 years to account for just 5% of total energy consumed in the United States and an additional 26 years to reach 25% [77]. Nuclear electricity took 38 years to reach a 20% share in the United States, which occurred in 1995. As Smil points out, “It’s taken between 50 and 70 years for a resource to reach a large penetration. When you look at the money, the infrastructure, the regulation, the technologies, it takes many decades for any fuel source to make a large impact [78]”.

At the global scale, we see even longer timeframes involved with energy transitions, illustrated by Fig. 2. Coal surpassed the 25% mark in 1871, more than five hundred years after the first commercial coalmines were developed in England. Crude oil surpassed the same mark in 1953, about nine decades after Edwin Drake drilled the first commercial well in Titusville, Pennsylvania, in 1859. Hydroelectricity, natural gas, nuclear power, and “other” sources such as wind turbines and solar panels still have yet to surpass the 25% threshold.

Assessing prime movers rather than fuels, Smil adds that steam engines were designed in the 1770s, but did not take off until the

¹ These five are modified into “seven” stages in Hughes later work. He split “invention” and “development” into separate phases and also added one on “innovation” after “development” and before “style.”

Table 3
Four key conceptual approaches to understanding energy transitions.

| | Socio-technical transitions | Ecological modernization theory | Sociology and social practice theory | Political ecology |
|------------------------------|---|---|---|---|
| Related academic disciplines | Science and technology studies, evolutionary economics, structuration theory | Environmental science, environmental sociology, policy studies | Sociology, anthropology, cultural theory | Human geography, ecology, political geography |
| Primary focus | The development or introduction of new technologies leading to new socio-technical configurations | Environmental regulation, reform, and governance | Everyday routines and practices | Conflict over natural resources and opposition to change |
| Themes | Transition pathways, momentum, path dependency, carbon lock-in, resistance by incumbents | Energy transitions, environmental reform, risk society, social movements | Changing practices, habits, socialization, normalization | Contestation, enclosure and exclusion, accumulation by dispossession, global production networks, neoliberalism |
| Units of analysis | Socio-technical systems, niches, regimes, and landscapes | Sectors, industries, institutions | Everyday practices or discourses | Ecological change, local communities, institutions |
| Selected key authors | Frank Geels, Johan Schot, Arie Rip, Frans Berkhout, René Kemp, Wim A. Smit, Thomas Hughes | Ulrich Beck, Maarten Hajer, APJ Mol, FH Buttel, Richard York, Martin Jaenicke | Elizabeth Shove, Gordon Walker, Loren Lutzenhiser, Harold Wilhite | David Harvey, Michael Watts, Paul Robbins, James McCarthy, Gavin Bridge |

Source: Modified from Ref. [76,171]

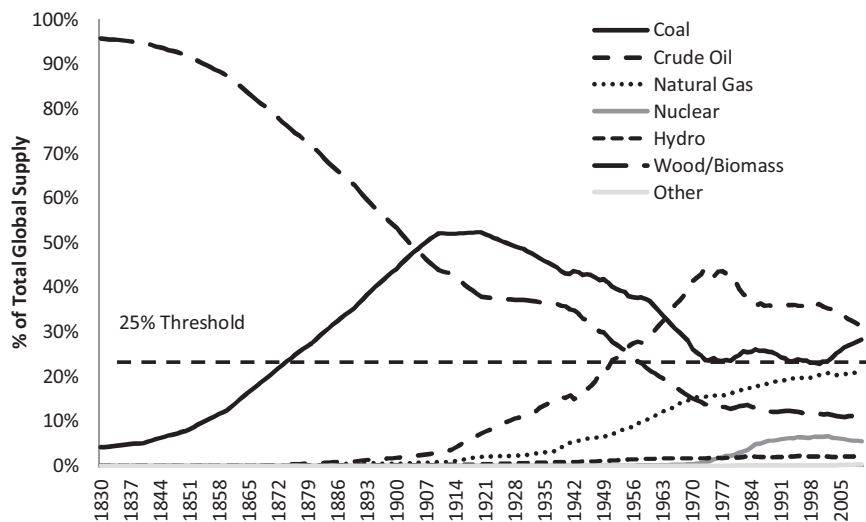


Fig. 2. Global Energy Supply by Fuel Source as a % of the Total, 1830–2010.

Note “Wood/Biomass” includes biofuels, and “Other” includes renewable sources of energy such as wind, solar, and geothermal.

Source: Modified from Refs. [79–81]

1800s, and the gasoline powered internal combustion engine, first deployed by Benz, Maybach, and Daimler in the middle of the 1880s, reached widespread acceptance in the United States only in the 1920s, even later for Europe and Japan. As Smil deduces from these examples, which tend to refer to large nations with high per capita energy use:

Energy transitions have been, and will continue to be, inherently prolonged affairs, particularly so in large nations whose high levels of per capita energy use and whose massive and expensive infrastructures make it impossible to greatly accelerate their progress even if we were to resort to some highly effective interventions... [81].

This is why he calls energy systems “a slow-maturing resource” and jokes that “energy sources, they grow up so ... slowly [77]”. Analogously, Fouquet studied various transitions between both energy fuels and energy services from 1500 to 1920, and found

that, on average, each single transition had an innovation phase exceeding 100 years followed by a diffusion phase approaching 50 years [82].

The argument that historical energy transitions are inherently lengthy events finds further support from energy analysts looking at the innovation or diffusion of prime movers or specific technologies. Lund, looking at prime movers, found that market penetration of new energy systems or technologies can take as long as 70 years [83]. Short “take-over times” of less than 25 years are limited to a few end-use technologies such as water heaters or refrigerators, and are not common for major infrastructural systems like those involving electricity or transport. Edmonds testified to U.S. senators that:

Given that it takes decades to go from “energy research” to the practical application of the research within some commercial “energy technology” and then perhaps another three to four decades before that technology is widely deployed throughout the global energy

market, we will likely have to [combat global warming] with technologies that are already developed [84].

Gorte and Kaarsberg also remark that research and development on energy technologies “usually takes years to pay off . . . the piper is paid five, ten, or more years in the future [85]”.

Thus, when many scholars conceptualize the temporal dynamics of a historical or even future transition, they presume that shifts and changes will take many, many years, since so many discrete alterations need to accumulate and align. As Smil remarks, “it is impossible to displace [the world’s fossil-fuel-based energy] super-system in a decade or two—or five, for that matter. Replacing it with an equally extensive and reliable alternative based on renewable energy flows is a task that will require decades of expensive commitment. It is the work of generations of engineers [77]”. In another article, Smil writes that “all energy transitions have one thing in common: They are prolonged affairs that take decades to accomplish, and the greater the scale of prevailing uses and conversions, the longer the substitutions will take [86]”. One review of fourteen historical transitions concluded that “the process from technological innovation to niche market to dominance took a minimum of 40 years” for single systems and that “an aggregate energy transition, involving the entire economy, could take centuries [87]”. As Grubler echoed in his review of the literature, “The fact that historical energy transitions have taken many decades, even above a century to unfold is a by now widely shared insight [88]”. Fouquet and Perason opine that energy transitions “have in the past tended to be relatively rare events whose complex and long drawn-out processes unfolded over decades and sometimes centuries [89]”. The Global Energy Assessment, a major international, interdisciplinary effort to better understand energy systems in 2012, notes that “transformations in energy systems” are “long-term change processes” on the scale of decades or even centuries [90]. This view holds that, as two Stanford University scientists write, “it appears that there is no quick fix; energy system transitions are intrinsically slow [91]”. Grubb et al. [92] Allen [93], and Rubio and Folchi [94] also each argue that energy transitions are gradual and sluggish processes that take upwards of 75 or even 130 years to occur. Fast transitions, when they occur at all, are considered anomalies, limited to countries with very small populations or unique contextual circumstances that can hardly be replicated elsewhere.

3. The timing of energy transitions: conflicting evidence

Contrary to the legitimate reasons and arguments presented in favor of the longevity of energy transitions, some empirical data suggests that under certain conditions, they can occur rather speedily. This data tends to support three arguments in favor of rapid transition: (1) we have seen fast transitions in terms of energy end-use and prime movers, (2) examples of rapid national-scale transitions in energy supply do populate the historical record, (3) the drivers of future transitions may differ fundamentally from the drivers of historical transitions; we can sufficiently learn from previous trends so that favorable future energy transitions can be expedited.

The first part of this section of the article explores no less than ten “quick” energy transitions – broadly defined – five of them focused on end-use devices such as lighting and air conditioning, five of them focused on national energy, electricity, or heating systems such as oil and electricity in Kuwait, cogeneration in Denmark, and nuclear power in France. Table 4 provides an overview of these cases, which collectively impacted more than 967 million people. As Araujo writes, “countries can, in fact, alter their energy balance in a significant way – stressing low carbon energy sources – in much less time than many decision-makers might imagine. Critical substitution shifts within [Brazil, France, Denmark, and Iceland]

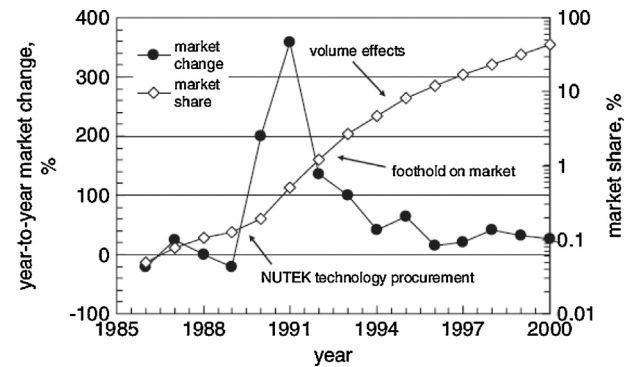


Fig. 3. Market Change and Market Share of Energy-Efficient Ballasts in Sweden, 1986–2000.

Source: Ref. [98]

were accomplished often in less than 15 years. Moreover, these transitions were effectuated even amidst circumstances at times involving highly complex energy technologies [95].

3.1. Rapid transitions in prime movers

At least five transitions in end-use devices, or prime movers, have occurred with remarkable rapidity: lighting in Sweden, cookstoves in China, liquefied petroleum gas stoves in Indonesia, ethanol vehicles in Brazil, and air conditioning in the United States.

Sweden was able to phase in an almost complete shift to energy efficient lighting in commercial buildings in about 9 years. Swedish Energy Authorities arranged for the procurement of high-frequency electronic ballasts for lights in office buildings, commercial enterprises, schools, and hospitals, which saved 30–70% compared to ordinary ballasts, in 1991 [96]. They used a multi-pronged approach of standardization and quality assurance, direct procurement, stakeholder involvement, and demonstrations to disseminate those ballasts. They began by collaborating with experts to develop a list of lighting quality factors for commercial buildings, and then asked for competitive tenders from manufacturers that met these standards. Then, the government directly purchased almost 30,000 units in a pilot phase, and worked with real estate management companies (for new buildings) and owners of public, commercial and industrial buildings (for retrofits) to ensure that they were installed [97]. After the pilot phase, they promoted distribution through government subsidies, sponsored demonstrations of the technology among the commercial sector, and involved consumer groups in discounted bulk purchases. Due to these concerted efforts, self-supporting volume effects were reached as early as 1996, catalyzing very rapid market penetration which jumped from about 10% that year to almost 70% by 2000 (the last year Lund analyzed)—growth exhibited by Fig. 3. In essence, this meant that between 1991 and 2000, 2.3 million Swedish workers experienced changes in the lights at their offices.

The Chinese Ministry of Agriculture sponsored an even more impressive National Improved Stove Program (NISP), managed by the Bureau of Environmental Protection and Energy (BEPE), from 1983 to 1998 [99,100]. The BEPE adopted a “self-building, self-managing, self-using” policy focused on having rural people themselves invent, distribute, and care for energy-efficient cookstoves, and it set up pilot programs in hundreds of rural provinces. From the start of the program until 1998, the NISP was responsible for the installation of 185 million improved cookstoves and facilitated the penetration of improved stoves from less than one 1% of the Chinese market in 1982 to more than 80% by 1998—reaching half a billion people, as Table 5 shows. The cookstoves being installed in China in 1994, during the height of the program,

Table 4
Overview of rapid energy transitions.

| Country | Technology/fuel | Market or sector | Period of transition | Number of years from 1 to 25% market share | Approximate size (population affected in millions of people) |
|-------------------------------|--------------------------------|----------------------------|----------------------|--|--|
| Sweden | Energy-efficient ballasts | Commercial buildings | 1991–2000 | 7 | 2.3 |
| China | Improved cookstoves | Rural households | 1983–1998 | 8 | 592 |
| Indonesia | Liquefied petroleum gas stoves | Urban and rural households | 2007–2010 | 3 | 216 |
| Brazil | Flex-fuel vehicles | New automobile sales | 2004–2009 | 1 | 2 |
| United States | Air conditioning | Urban and rural households | 1947–1970 | 16 | 52.8 |
| Kuwait | Crude oil and electricity | National energy supply | 1946–1955 | 2 | 0.28 |
| Netherlands | Natural gas | National energy supply | 1959–1971 | 10 | 11.5 |
| France | Nuclear electricity | Electricity | 1974–1982 | 11 | 72.8 |
| Denmark | Combined heat and power | Electricity and heating | 1976–1981 | 3 | 5.1 |
| Canada (Ontario) ^a | Coal | Electricity | 2003–2014 | 11 | 13 |

^a The Ontario case study is the inverse, showing how quickly a province went from 25% coal supply to zero.

Table 5
Households adopting improved stoves under the Chinese NISP and affiliated provincial programs.

| | NISP households (million) | Households under provincial programs (million) | Total households/year (million) | Total people/year (million) |
|-----------|---------------------------|--|---------------------------------|-----------------------------|
| 1983 | 2.6 | 4 | 6.6 | 21.1 |
| 1984 | 11 | 9.7 | 20.7 | 66.2 |
| 1985 | 8.4 | 9.5 | 17.9 | 57.3 |
| 1986 | 9.9 | 8.5 | 18.4 | 58.9 |
| 1987 | 8.9 | 9.1 | 18 | 57.6 |
| 1988 | 10 | 7.5 | 17.5 | 56 |
| 1989 | 4.5 | 5 | 9.5 | 30.4 |
| 1990 | 3.6 | 7.8 | 11.4 | 36.5 |
| 1991–1998 | 7.8 | 57.2 | 65 | 208 |
| Total | 66.7 | 118.3 | 185 | 592 |

Source: Ref. [100]

were equivalent to 90% of all improved stoves installed globally. As a consequence, although substitution was never complete—all existing inefficient cookstoves were never replaced, just most of them—Chinese energy use per capita declined in rural areas at an annual rate of savings of 5.6% from 1983 to 1990.

Indonesia also ran a large household energy program focusing on the conversion from kerosene stoves to liquefied petroleum gas (LPG) stoves to improve air quality. Under leadership from their Vice President Jusuf Kalla, the Indonesian “LPG Megaproject” offered households the right to receive a free “initial package” consisting of a 3 kg LPG cylinder, a first free gas-fill, one burner stove, a hose, and a regulator. The government, in tandem, lowered kerosene subsidies (increasing its price) and constructed new refrigerated LPG terminals to act as national distribution hubs. Amazingly, in just 3 years – from 2007 to 2009 – the number of LPG stoves nationwide jumped from a mere 3 million to 43.3 million, meaning they served almost two-thirds of Indonesia’s 65 million households (or about 216 million people). Six entire provinces, including that of Jakarta, the capital, were declared “closed and dry”, meaning that the program reached all of its targets, and that all kerosene subsidies were withdrawn [101].

Brazil has perhaps the fastest energy transition on record, though (to be fair) it depends on what one counts. Brazil created its Proálcool program in November 1975 to increase ethanol production and substitute ethanol for petroleum in conventional vehicles, and in 1981, six years later, 90% of all new vehicles sold in Brazil could run on ethanol—an impressive feat. However, a more recent transition, connected in part to the Proálcool program, is even more noteworthy. The Brazilian government started incentivizing flex-fuel vehicles (FFVs) in 2003 through reduced tax rates and fuel taxes. These Brazilian FFVs were capable of running on any blend of ethanol from 0 to 100%, giving drivers the option of switching between various blends of gasoline and ethanol depending on price and convenience. The first year FFVs entered the market in 2004

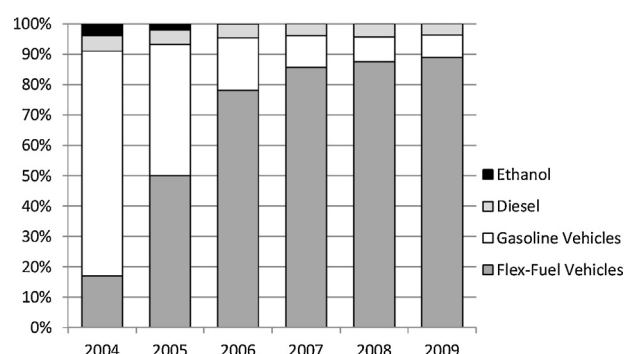


Fig. 4. Flex-Fuel Vehicle Sales as a Percentage of Overall New Car Sales in Brazil, 2004–2009.

Source: Modified from Ref. [102]

they accounted for 17% of new car sales but they rapidly jumped to 90% in 2009—as Fig. 4 illustrates—meaning 2 million FFVs were purchased in total over the first five years of the program [102].

Air conditioning in the United States is a final example. In 1947, mass-produced, low-cost window air conditioners became possible, enabling many people to enjoy air conditioning without the need to buy a new home or completely renovate their heating system [103]. That year, only 43,000 units were sold, but by 1953 the number had jumped to one million, as air conditioners became endorsed by builders eager to mass produce affordable, yet desirable, modern homes and electric utilities that wanted to increase electricity consumption throughout the growing suburbs [104]. Consequently, more than 12% of people (occupying 6.5 million housing units) reported to the U.S. Census in 1960 that they owned an air conditioner, rising to 25% in 1963 and 35.8% in 1970, representing 24.2 million homes and more than 50 million people [105,106]. Since then, the presence of air conditioning in single-

family homes jumped from 49% in 1973 to 87% in 2009 [107]. In hot and humid places such as Southern Florida, its use grew from five percent in 1950 to 95% in 1990. American motorists also use up 7–10 billion gallons of gasoline annually to air condition their cars. In aggregate, the United States on an annual basis now consumes more electricity for air conditioning than the entire continent of Africa consumes for all electricity uses [108]. Or, in other terms, the United States currently utilizes more energy (about 185 billion kWh) for air-conditioning than all other countries' air conditioning usage combined [109].

3.2. Rapid transitions in energy supply

Empirical data also points to five other transitions in supply that have occurred at the national level: to crude oil and electricity in Kuwait, natural gas in the Netherlands, nuclear electricity in France, combined heat and power in Denmark, and coal retirements in Ontario, Canada.

Two concurrent modifications, in electricity and transport, catalyzed an almost complete shift in Kuwait's national energy profile in about 9 years. Oil use catapulted from constituting a negligible amount of total national energy supply in 1946 to 25% in 1947 and above 90% in 1950 [110]. In 1938, when Kuwait was still a small, impoverished British protectorate, geologists discovered the Burgan oilfield, which proved to be the world's second largest accumulation of oil following Saudi Arabia's Ghawar oil field [111]. Commercial exploitation began in earnest in 1946 after a suspension of operations due to World War II, increasing from 5.9 million barrels that year to 16.2 million barrels in 1947 and almost 400 million barrels in 1955, in tandem with the development of other oil fields [112]. Within five years – 1945 to 1949 – the Kuwaiti oil industry was transformed from one dependent on five gallon barrels being distributed manually to customers, carried on camels, donkeys, or wooden push carts to one characterized by huge volumes and scale economies that were dependent on motorized trucks and tankers, pipelines, and filling stations [113].

Simultaneously, Kuwait began using oil for electricity generation. The Kuwait Oil Company obtained and commissioned its first 500 kW generator in 1951 and in 1952 built a 2.25 MW Steam Power Station at Al-Shewaikh, essentially tripling national electricity capacity in three years [114]. Demand for such electricity grew considerably, doubling again by 1960 and then increasing (in per capita terms) from about 1500 kWh to more than 9200 kWh in 1985 [115]. Thereafter a rapid expansion of distillation units, refineries, petrol stations, and the establishment of the Kuwait National Petroleum Company in 1960, the same year Kuwait helped form the Organization of Petroleum Exporting Countries, saw oil's rise continue so that in 1965 Kuwait became the world's fourth largest producer of oil (behind the United States, USSR, and Venezuela, and ahead of Saudi Arabia) [81]. As even energy transition skeptic Smil concedes, "in energy terms Kuwait thus moved from a pre-modern society dependent on imports of wood, charcoal, and kerosene to an oil superpower in a single generation [81]".

The Netherlands—thanks in large part to the discovery of a giant Groningen natural gas field in 1959—started a rapid transition away from oil and coal to natural gas [81]. That year, coal supplied about 55% of Dutch primary energy supply followed by crude oil at 43% and natural gas less than 2%. In December 1965, however, one year after gas deliveries began from Groningen, natural gas supplied 5% of the Netherlands' primary energy, rising quickly to 50% by 1971. To facilitate the transition, the government decided in December 1965 to abandon all coal mining in the Limburg province within a decade, doing away with some 75,000 mining related jobs impacting more than 200,000 people. What made the transition successful was that the government strategically steered it [116], implementing countermeasures such as subsidies for new businesses, the

relocation of government industries from the capital to regions of the country hardest hit by the mine closures, retraining programs for miners, and offering shares in Groningen to Staatsmijnen (the state mining company). After its peak output in the mid-1970s, extraction of gas at Groningen was purposely scaled back to maximize the lifetime of the field, though natural gas continued to play a prominent role in the nation's energy mix. In 2010, for instance, natural gas still provided 45% of total primary energy supply, larger than any other source [117].

The French transition to nuclear power was also swift. Following the oil crisis in 1974, Prime Minister Pierre Messmer announced a large nuclear power program intended to generate all of France's electricity from nuclear reactors to displace the Republic's heavy dependence on imported oil. As the maxim went at the time, "No coal, no oil, no gas, no choice! [95]". The "Messmer Plan" proposed the construction of 80 nuclear power plants by 1985 and 170 plants by 2000. Work commenced on three plants – Tricastin, Gravelines, and Dampierre – immediately following the announcement of the plan and France ended up constructing 56 reactors from 1974 to 1989. As a result, nuclear power grew from 4% of national electricity supply in 1970 to 10% in 1978 and almost 40% by 1982. As Grubler has noted, "the reasons for this success lay in a unique institutional setting allowing centralized decision-making, regulatory stability, dedicated efforts for standardized reactor designs and a powerful nationalized utility, EDF, whose substantial in-house engineering resources enabled it to act as principal and agent of reactor construction simultaneously [118]".

Though Denmark is perhaps more famous for a transition to wind energy, a far more accelerated transition occurred in the 1970s and 1980s. This transition involved two sets of changes, from oil to coal as a fuel for electricity and from individual to district heating in heating. Before 1974, almost all heating in Denmark was provided by fuel oil, which meant the oil crisis had particularly painful impacts on the country's economy [119]. The Danish Energy Policy of 1976 therefore articulated the short-term goal of reducing oil dependence, and it stated the importance also of building a "diversified supply system" and meeting two-thirds of total heat consumption with "collective heat supply" by 2002. Moreover, it sought to reduce oil dependence to 20%, an ambitious goal that involved the conversion of 800,000 individual oil boilers from natural gas and coal. In a mere five years – from 1976 to 1981 – Danish electricity production changed from 90% oil-based to 95% coal-based. Stipulations in favor of combined heat and power (CHP) were further strengthened by the 1979 Heat Supply Act, whose purpose was to "promote the best national economic use of energy for heated buildings and supplying them with hot water and to reduce the country's dependence on mineral oil". As a result, CHP production increased from trivial amounts in 1970 to supply 61% of national electricity and 77% of the country's district heating in 2010.²

A final example is intriguing because rather than transitioning towards something, it involves transitioning away. In 2003, the government of Ontario committed to retiring all coal-fired electricity generation by 2007, something they did accomplish, albeit a few years behind schedule. Ontario's oldest coal plant, the 1140 MW Lakeview facility, was closed in April 2005 followed by sequential closures of Thunder Bay (306 MW), Atikokan (211 MW), Lambton (1972 MW), and Nanticoke (3945 MW) from 2007 to 2014. Coal generation thus declined from 25% of provincial supply in 2003 to 15% in 2008, 3% in 2011, and 0% in 2014. The primary justification

² As an aside, national planners managed a third transition, away from coal, in the 1990s, when the Danish parliament passed the "coal stop," functionally outlawing the construction of new coal fired power stations, with exceptions given only to two 450 MW plants.

for the closure, apart from its obvious climate change benefits, was public health. A government study estimated that shifting away from coal would reduce some 330,000 related illnesses and more than 700 deaths related to coal pollution to fewer than 6 deaths and only 2460 illnesses. Put into monetary terms, the “coal switch” was estimated to save \$4.4 billion per year in health, environmental, and financial damages along with \$95 million in displaced operating and maintenance costs [120]. To achieve this transition, Ontario invested more than \$21 billion in cleaner sources of energy including wind, hydroelectricity, solar, and nuclear power, as well as \$11 billion in transmission and distribution upgrades and other investments in energy efficiency [121]. Ontario is on track to see renewable sources of electricity grow to 46% of supply by 2025, and typical residential customers are expected to save \$520 on their bills, and large industrial customers to save \$3 million each on their bills, from 2013 to 2017 [121].

3.3. Re-conceptualizing the temporal dynamics of future transitions

The ten examples above—five covering prime movers, five covering changes in supply—do cast some doubt on mainstream conceptions that transitions must invariably take decades to occur. Indeed, although previous, historical transitions may have taken a great deal of time, the argument runs that we have learned a sufficient amount from them so that contemporary, or future, energy transitions can be expedited. Future transitions may also become a social or political priority in ways that previous transitions have not been—that is, previous transitions may have been accidental or circumstantial, whereas future transitions could become more planned and coordinated, or backed by aggressive social movements or progressive government targets. This section of the paper discusses three significant drivers behind the possibility of accelerated future transitions: scarcity, climate change, and innovation.

First, unlike earlier transitions driven primarily by price or an abundance of resources, future ones may be driven by scarcity and the unaffordability of resources. Consider crude oil. Sorrel et al. examined oil field-size, reserve growth and decline rates, and depletion rates for the entire industry [122]. They concluded that, as a global average:

The (reserve diminishment) rate of post-peak fields is at least 6.5%/year and the corresponding decline rate of all currently producing fields is at least 4%/year. Both are on an upward trend as more giant fields enter decline, as production shifts towards smaller, younger and offshore fields and as changing production methods lead to more rapid post-peak decline. More than two thirds of current crude oil production capacity may need to be replaced by 2030, simply to keep production constant. At best, this is likely to prove extremely challenging.

Numerous other studies suggest that resource peaks are imminent, if not already present. One assessment of the “most likely scenarios” estimated that global oil production peaked in 2015, that natural gas production would peak in 2035, and that coal production would peak in 2052—forming the bell-shaped curves in production illustrated by Fig. 5 [123]. Similar peaks in supply have been confirmed by multiple, independent analyses undertaken by some of the world’s best geologists, economists, and energy analysts for oil and natural gas [124–128], coal [129–136], and even uranium [137,138]. British Petroleum, hardly a source biased against fossil fuels, estimated in 2014 that global reserve to production ratios for oil, natural gas and coal were 53.3 years, 55.1 years and 113 years, respectively [139].

Even if such peaks in supply are exaggerated or uncertain, there is also the possibility of peaks in demand—of demand-driven scarcity. Put another way, “demand peaks” can quickly exert change

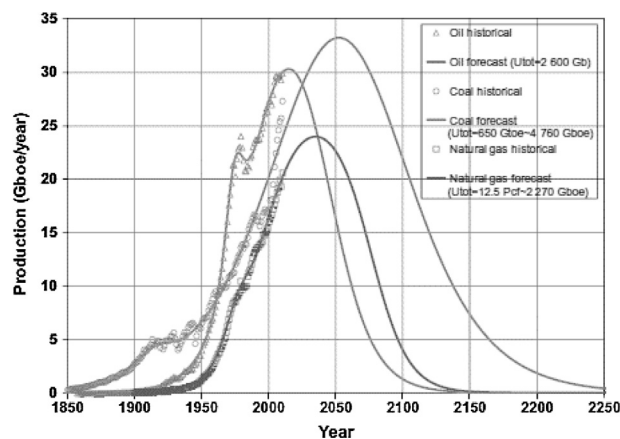


Fig. 5. Projected Global Peaks in Production for Oil, Gas, and Coal, 1850–2250. Source: Ref. [140]

on “supply-side” energy technologies, altering their configurations in ways unheard of before. Many studies support such a contention about rapid shifts in demand for fossil fuels. One research team, for instance, predicted that the inflated prices for petroleum that are expected this century could practically bankrupt the iron, fertilizer, and air transport industries [141]. Citi Bank, a global financial firm, declared in 2013 that global oil demand was “approaching a tipping point” and that “the end is nigh” for growth due to substitution trends of natural gas for oil coupled with improvements in the fuel economy of vehicles [142].

Second, speedy future transitions may be necessary to avoid the social and environmental costs stemming from unabated climate change. This second major driver relates to environmental carrying capacity limits. Whether we choose to acknowledge it or not, proponents of this view hold that humanity must undertake economic activities subject to a “carbon budget.” At a certain level of greenhouse gas emissions, we cannot afford to utilize more fossil fuels, even if they were free [143]. As Hansen and his colleagues have noted, “Burning all fossil fuels would produce a different, practically uninhabitable, planet [144]”. Thus, many barrels of oil, cubic meters of natural gas, and tons of coal will need to stay in the ground as “stranded assets [145,146]”. One study examined the volumes of oil that “cannot be used” by 2035 due to carbon restraints and projected that 500–600 billion barrels must be “unburnable” and that 40–55% of new deep-water resources must not be developed [147]. Even if geologic or economic peaks were avoidable, these folks argue, the threat of climate change forces a retreat from fossil fuel consumption [126]—it requires a fast, and eventually complete transition.

Third, technological learning and innovation can result in new technologies and systems with the potential for exponential growth. Former United States Vice President Al Gore encapsulated this type of thinking when he argued, in 2008, that “today I challenge our nation to commit to producing 100% of our electricity from renewable energy and truly clean carbon-free sources within 10 years [148]”. Gore went on to say that a complete change in energy production was “achievable, affordable and transformative” within the course of one decade. His thinking rested on the assumption that innovations in both technology and policy design can accelerate technological change, and achieve an energy transition, in ways not possible even just a few decades ago.

For example, previous transitions such as that from wood to coal or coal to oil occurred without the accumulation of knowledge we have currently about the sociology, politics, and economics of energy transitions, i.e., without the complex historical analyses conducted by the likes of Smil, Grubler, Wilson, Hughes, and Fou-

quet. Because we now possess this knowledge, we can apply it going forward to minimize the unnecessary lag or delay of a future energy transition. Even Fouquet and Perason write that “past energy transitions may not be the best analogies for a future low carbon energy transition [149]”. Why? In part, we now possess better knowledge about the co-benefits of low-carbon supply including less air pollution and improved public health, economic diversification, and enhanced national competitiveness [150–152]. We have better causal models and analysis of how transitions occur and are beginning to establish methodologies and policy prescriptions for how to manage future transitions [153–157]. We now have newly developed policy mechanisms such as production tax credits, feed-in tariffs, and renewable portfolio standards that can hasten the adoption of preferred technologies [158]. And, many newer energy technologies can provide multiple energy services at once, such as microhydro dams (which can provide mechanical energy for agricultural processing, electricity, and irrigation simultaneously) [159], TEG cookstoves (which can provide both heat for cooking and small amounts of electricity) [160] or tri-generation (electric generators that can provide electricity, heat, and cooling at the same time) [161]. Each of these new systems can replace two or three previously distinct devices, and operate more like general purpose technologies.

For these reasons, perhaps future energy transitions, because they can draw on synergistic advances in multiple domains at once—cutting across multiplicity of energy services, materials science, computing, combustion dynamics, gasification, nanotechnology, biological and genetic engineering, 3D printing and the industrial internet—can truly be accelerated in ways that past transitions have (generally) not been, despite the fact that it may be scarcity or concerns about climate change, rather than abundance or price, driving them. “Accelerated diffusion” can become the norm, not the exception.

4. Conclusion and policy implications

This final part of the paper offers four conclusions for energy analysts and practitioners.

First, at a basic level, whether an energy transition can occur quickly or slowly can depend in great deal about how it is defined. Some core definitional issues include:

- Different interpretations of “significant”. Significance may presume large absolute magnitude or share with respect to a particular energy sector (narrow such as cooking and household electricity, or new commercial lighting systems, or broad such as entire energy supply or all buildings). Significance can also be subjective, with good social science usually asking “significant for whom?”;
- Different interpretation of “in a society”. This may refer to the world as a whole, a group of countries, one country (small or large), part of a country (Ontario) or a particular segment of population (e.g. low-income peasants in China, new car purchasers in Brazil, office workers in Sweden);
- Different interpretations of “resources, carriers, converters and services”. Many historic analyses of energy transitions looked for situations when all of these were significantly affected (e.g. substituting coal with oil affected not only the type of minerals being extracted, but also distribution infrastructure, refining, types of vehicles and engines, mobility patterns of population heating, electricity generation, urban development, etc.). In contrast, switching from kerosene to LPG in Indonesia had a much more confined effect on resources, carriers, converters and services. Switching to FFVs in Brazil did not affect services and converters (FFVs have a similar engine) and may or may not affect

resources or carriers (depending on whether people fill their FFVs with conventional fuel or alcohol).³

Such definitional assumptions and demarcations are not always clear in the academic literature, yet they are important, for they capture how transitions are framed and also propagated rhetorically to the public [162].

Second, timing of a transition can be subjective. Sometimes the “speed” at which an energy transition occurs has less to do with what actually happened and more to do with what or when one counts [163]. The American transition to oil, according to Smil, took about 80 years to reach a 25% share, yet during the most accelerated phase of that transition—from 1990 to 1925—oil grew from 2.4% of national energy supply to 24%, justifying those who would call it “quick [164]”. For air conditioning, whether one takes the time of first conception (Nikola Tesla developed electric motors that made possible the invention of oscillating fans in 1885), first invention (Willis Carrier invented the first modern system in 1902), or first successful commercial application (when Henry Galsion developed an affordable mass produced system in 1947) greatly alters the perceived rate of market penetration [165]. Brazil’s transition to flex-fuel vehicles, arguably, took a year (from the start of the national program to large-scale diffusion), more than twenty years (from the first invention of a FFV in 1980), almost thirty years (from the start of their national ethanol program), or more than eight decades (from the first invention of a Brazilian engine capable of using ethanol in the 1920s).

In the case of national transitions, we see similar ambiguity. Kuwait’s transition to oil can be said to have begun in 1934, with the first concession given to the Kuwait Oil Company; or in 1937, when the first exploratory wells were drilled in the Burgan field; or in 1946, when commercial production began (the starting point taken here); or even in 1949, when the first refinery was established. Similarly the French nuclear power program could have defensibly begun in 1942 with the first chain reaction under the Manhattan project; or in 1945, with the formation of the Commissariat à l’Énergie Atomique; or in 1948, when their first research reactor was commissioned; or in 1974 with the launch of the Messmer Plan (taken here). Deciding what one counts includes within it normative assumptions about what an energy transition is; the problem is that analysts do not always make these assumptions transparent.

Third, adding to the difficulty of defining and dating them, energy transitions are complex, and irreducible to a single cause, factor, or blueprint. They can be influenced by endogenous factors within a country, like aggressive planning in China, Denmark, Indonesia, the Netherlands, Ontario or Sweden, intensified by political will and stakeholder involvement, or exogenous factors outside of a country, such as military conflict (the World Wars spawning the French nuclear program, their cessation enabling Kuwait to invest in oil fields), a major energy accident (Chernobyl, Fukushima), or some global crisis (the oil shocks of the 1970s, the collapse of communism in the early 1990s, climate change today). Other transitions, such as the adoption of air conditioning, can be almost entirely market driven. Some can offer financial or social benefits to early adopters—cooler homes for the owners of air conditioning, improved health for cookstove users, savings at the pump for FFV drivers—whereas others (such as nuclear power in France, oil in Kuwait, and natural gas in the Netherlands) primarily diffused their benefits to governments and private corporate actors in the form of economic rents. Put another way, some transitions were quick

³ Also, the Brazilian case is rather incremental technological substitution rather than systemic change towards a more sustainable transport system involving walking, cycling, integration of multi-modal forms of transport, and so on.

because they were managed or incentivized; others were more naturally occurring as a function of changes in technology, price, or consumer demand. Some benefited homeowners or consumers, others benefitted corporations or governments.

This makes each of the ten rapid case studies examined unique and context dependent. Some were about discrete artifacts (e.g. stoves, air conditioners, cars), which are perhaps easier to diffuse than entire systems. Quite a few are in small countries: Denmark, Kuwait, the Netherlands, Ontario and Sweden. Many have special governance characteristics: communist China, Brazil under military dictatorship, Sweden with a corporatist economy, Denmark and its socialist communes, and centrally planned France. Some were based on special natural resource discoveries: natural gas in Denmark and the Netherlands, oil in Kuwait, wind, solar and hydro potential in Ontario. Each case has certain specificities that help explain the rapidity of transition.

The implication here is that energy transitions have no magic formula. The United Kingdom, for instance, had the same access to natural gas that the Netherlands did, yet it was unable to cultivate the same type of changeover [81]. Countries throughout the Asia-Pacific have access to the same LPG stove technology that exists in Indonesia but have not seen widespread adoption [166]. The experience of tiny, affluent countries such as Denmark and Kuwait may be relevant for countries in a similar class (such as Belgium, Brunei, or Qatar), but less so for an India or Nigeria. Moreover, the sociocultural or political conditions behind transitions in Brazil and China, at the time military dictatorships and communist regimes (respectively), are incompatible with the governance norms espoused in modern democracies across Europe and North America. Furthermore, history seems to suggest that past transitions—including many of the case studies presented here—are based on discoveries of new, significant, and affordable forms of energy (usually carbon-intensive) or technology, leading to abundance. Yet in the future, it may be scarcity and “stranded assets,” rather than abundance, which influences decisions [167].

Fourth, and lastly, is that given these attributes of complexity, timing, and causality, most energy transitions have been, and will likely continue to be, path dependent rather than revolutionary, cumulative rather than fully substitutive. To use parlance from the multilevel perspective and sociotechnical transitions theory, niches will only rarely evolve to completely dominate a landscape. Older sources of energy—such as muscle power, animate power, wood power, and steam power—still remain in use throughout the world today, they have not entirely been replaced by fossil, nuclear, and modern renewable energy [168,169]. Grubler himself writes that “In fact, a new solution does not evolve in a vacuum but interacts with existing practices and technologies [37]”. One analyst at MIT commented that “we’ll use renewable energy more as technology makes it cheaper, but we’re likely to keep using more of the other sources of energy, too [170]”. The motorized automobile behind (in part) the transition to oil in Kuwait and FFVs in Brazil is actually a consolidation of earlier inventions fused together: the internal combustion engine, the wheel, the casting of steel, electric lights, tires, the assembly line, and so on. The CHP, biomass, wind, and solar technology behind the transitions in Denmark and Ontario have benefitted from advances in the fossil-fuel chain including combined cycle turbines, batteries, and compressed air energy storage.

Thus, transitions often appear not as an exponential line on a graph, but as a punctuated equilibrium which dips and rises. Fast transitions have occurred and are capable of occurring, but they only become apparent when one carefully adheres to a particular notion of significance, society, energy resources, and energy services, and then appreciates contextual specificity. Future energy studies, forecasts, and scenarios ought to make these attributes much more transparent and explicit.

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